Developing ISM Dust Grain Models with Precision Elemental Abundances from IXO

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Abstract

The exact nature of interstellar dust grains in the Galaxy remains mysterious, despite their ubiquity. Many viable models exist, based on available IR-UV data and assumed elemental abundances. However, the abundances, which are perhaps the most stringent constraint, are not well known; modelers must use proxies in the absence of direct measurements for the diffuse interstellar medium (ISM). Recent revisions of these proxy values have only added to confusion over which is the best representative for the diffuse ISM, and highlighted the need for direct, high signal-to-noise measurements from the ISM itself. The International X-ray Observatory's superior facilities will enable high-precision elemental abundance measurements. We will show how these results will measure both the overall ISM abundances and challenge dust models, allowing us to construct a more realistic picture of the ISM.

Introduction

Interstellar dust grain models rely heavily on constraints provided by the measured UV/optical absorption and scattering, IR emission, and polarization, and the assumed dust-phase elemental abundances. However, several models exist which can satisfy these constraints (Zubko et al. 2004), so additional limits must be placed on models so that we may distinguish among them. An obvious choice is to better determine the dust-phase elemental abundances. Until now, the most common method has been through indirect measurement: measuring the gas-phase abundances and subtracting them from the assumed total (solid + gas phase) ISM abundances (so-called "cosmic" abundances), with the result being the amount that is locked away in dust particles. The gas-phase component of the local ISM is fairly well-known (Cardelli et al. 1996; Sofia et al. 1997; Cardelli & Meyer 1997; Sofia et al. 1998) and seems relatively constant; however, the total ISM elemental abundances are not known, and proxies are often used instead.

Historically, the Sun has been used as the standard for ISM abundances. However, while most solar abundances have remained more or less constant over the years, those of the main dust-forming elements have dropped considerably (Anders & Grevesse 1989; Grevesse & Sauval 1998; Asplund et al. 2005), as seen in Fig. 1. With the latest revision downward, solar O abundances are now in better agreement with those of B stars (Sofia & Meyer 2001; André et al. 2003; Asplund et al. 2005), which have been thought to better represent the ISM, but there is now far too little material in the solid phase for the models to reproduce the observables (Li 2005). Further, B stars are subject to element stratification due to diffusion, so abundances measured at their surfaces do not necessarily reflect the abundances of the clouds from which they formed.

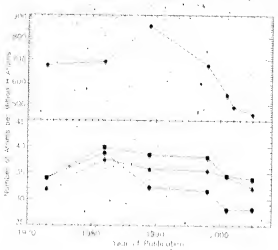

Fig. 1 Solar abundances over time. Top: O. Bottom: Fe (circles,) Mg (squares), Si (triangles).

X-ray spectroscopy offers a way out of the quagmire with direct measurements of gas and solid phase abundances, letting us tightly constrain dust grain models without introducing the uncertainties that are inevitable when using indirect methods. This has been done with data from Chandra and XMM-Newton (e.g. Paerels et al. 2001; Takei et al. 2002; Juett et al. 2004; Ueda et al. 2005) but there is significant variation in the results. Some of these spectra have anomalous abundance ratios, indicative of circumstellar material, making them poor representatives of the diffuse ISM. Others have uncertainties which are too large to provide meaningful constraints on grain models.

The Importance of IXO

High signal-to-noise measurements coupled with multiwavelength data along diffuse ISM sightlines are crucial to building comprehensive grain models. IXO will provide high quality observations of the absorption edges of dust-forming elements, in short exposure times. Fig. 2 compares modeled spectra from Chandra, XMM, and IXO of the nearby HMXRB X Per (modeled with a power law: $N_H = 2\times10^{21}$ cm^{-1}, $\gamma = 1.1$, flux = 10^{-10} erg s^{-1} cm^{-2}). Exposure times are as indicated. Even assuming the very low solar abundances of Wilms et al. (2000), IXO (Ucal) can recover O, Mg, Si, and Fe abundances to better than 10% (Table 1).

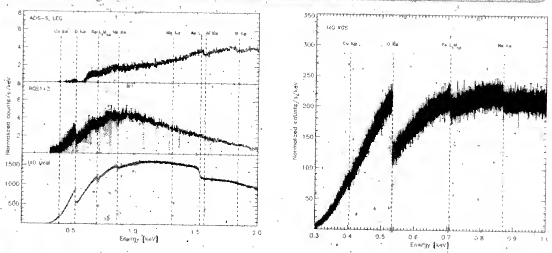

Fig. 2. Comparison of the modeled spectrum of X Per obtained with different X-ray observatories. Left: Top: Chandra ACIS-S, LEG (t = 50 ks); Middle: XMM-Newton RGS (t = 50 ks); Bottom: IXO Ucal (t = 20 ks). Right: IXO XGS (t = 50 ks).

IXO's large effective area will greatly increase the number of sightlines where such spectroscopy can be done. Over 1800 sources have fluxes high enough to allow determination of the abundances to O, Mg, Si, and Fe to within 20% uncertainty; this is sufficient to distinguish between grain models, as can be seen in Table 2. These sightlines are plotted in Fig. 3. With numerous bright Galactic sources, this will also provide valuable information on the chemical uniformity of the ISM; mixing, and chemical enrichment. Further, IXO's exquisite resolution will allow us to examine X-ray absorption edge fine structure, which will let us determine the chemical states the elements are in, thus imposing further constraints on grain composition.

	Chandra	XMM	IXO
O	1.02 ± 0.28	1.05 ± 0.13	1.00 ± 0.00
Mg	0.81 ± 0.78	1.62 ± 1.06	1.02 ± 0.04
Si	0.48 ± 0.48	0.23 ± 0.23	0.91 ± 0.07
Fe	1.03 ± 0.83	0.78 ± 0.42	1.01 ± 0.01

Table 1. Percent solar abundances recovered from fit of modeled X Per spectrum.

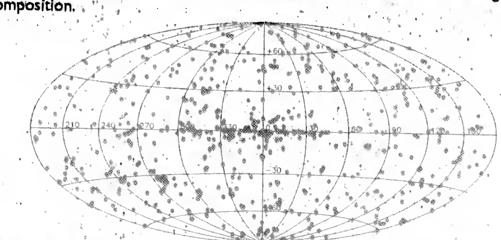

Fig. 3. Sightlines for which IXO will be able to determine abundances of silicate-forming elements to better than 20%.

IXO will be able to examine abundances in different environments in the ISM, thus opening a window on the study of grain evolution and cycling between diffuse and dark clouds. In Fig. 4, we have plotted the percent error of abundance measurements for a source, modeled again as X Per, with exposure times of 50 ks for Chandra and XMM, and 20 ks for IXO. We used the solar abundances of Wilms et al. (2001) and set N_H to different values: 5×10^{21}, 5×10^{22}, and 5×10^{23} cm^{-2}. The uncertainties for Chandra and XMM tend to be around 20% or higher, even along relatively diffuse sightlines; as the density increases, the uncertainty does as well, to 100% in many cases. Along very dense sightlines ($N_H = 5\times10^{23}$ cm^{-2}), XMM cannot detect any of these elements in the given exposure time. In stark contrast, the uncertainties with IXO are far lower -- less than 3%, for both diffuse and dense sightlines.

IXO will provide us with high precision data, over a wide range of environments, that has not been available with previous missions. By providing us with high quality abundances, both total and gas/solid phases, over a wide range of environments, IXO will revolutionize interstellar dust modeling.

Element	(1)†	(2)†	(3)	(4)†	(5)†	(6)
O	124	444	136	145	160	146
Mg	33	33	37	36	20	36
Si	31	30	33	35	40	36
Fe	26	26	30	42	20	36

Table 2. Number of atoms per 10^6 H atoms needed by varius dust models. (1) Mathis et al. 1977; (2) Hong & Greenberg 1980; (3) Draine & Lee 1984; (4) Chlewicki & Laureijs 1988; Désert et al. 1990; (6) Weingartner & Draine 2001. †From Snow & Witt 1996.

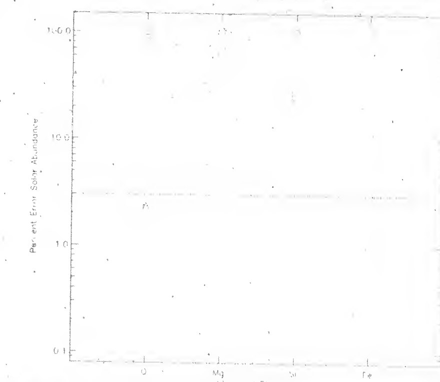

Fig. 4. Percent errors in abundance measurements of silicate grain-forming elements assuming solar abundances from Wilms et al. (2001), in spectra from Chandra ACIS-S, LEG (circles), XMM-Newton RGS (squares) and IXO Ucal (triangles) when N_H is 5×10^{21} cm^{-2} (yellow), 5×10^{22} cm^{-2} (orange), and 5×10^{23} cm^{-2} (red). Exposure times were 50 ks for Chandra and XMM, and 20 ks for IXO. The dotted line indicates 3% error.

References: Anders & Grevesse 1989, GeCoA, 53, 197; Andre et al. 2003, ApJ, 591, 1000; Asplund et al. 2005, ASPC, 336, 25; Cardelli et al. 1996, ApJ, 467, 334; Cardelli & Meyer 1997, ApJ, 477, L57; Chlewicki & Laureijs 1988; Désert et al. 1990; Draine & Lee 1984, ApJ, 285, 89; Grevesse & Sauval 1998, SSRv, 85, 161; Hong & Greenberg 1980, A&A 88, 194; Juett et al. 2004, ApJ, 612, 308; Li 2005, ApJ, 622, 965; Mathis et al. 1977, ApJ, 217, 425; Paerels et al. 2001, ApJ, 546, 338; Snow & Witt 1996, ApJ, 468, L65; Sofia et al. 1997, ApJ, 482, L105; Sofia et al. 1998, ApJ, 504, L47; Sofia & Meyer 2001, ApJ, 554, L221; Takei et al. 2002, ApJ, 581, 307; Ueda et al. 2005, ApJ, 620, 274; Weingartner & Draine 2001, ApJ, 548, 296; Wilms et al. 2000, ApJ, 542, 914; Zubko et al. 2004, ApJS, 152, 211